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A Methodology for Designing Airports for Enhanced Security Using Simulation

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Abstract

With the advent of the new security measures, today's airports have become increasingly complex and congested. Air and passenger traffic continues to increase; consequently, the need for intelligent design concepts is required. Unlike all other existing airport designs that focused exclusively on operational performance, this study focused on the development of a new airport terminal design methodology that takes a proactive approach to minimizing the effects of security disruptions while simultaneously maximizing operational performance and passenger flow. The study addressed the impact of security operations on both the design of airport facilities and passenger flows, and discussed options and scenarios to integrate these factors in obtaining improved performance. Simulation analysis results revealed that alternative designs can result in cost savings from evacuation time reductions of up to 10%.

Keywords: airport security, simulation

Introduction

Airport facilities face enormous challenges, especially in terms of their capability to adjust to incessant demands, increasing passenger expectations, and security requirements. In the aftermath of recent terrorist threats and attacks (most notably 9/11), airports are consistently experiencing modifications in functions, and new terminal designs evolve because of operational changes dictated by increased security measures.

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These security breaches have caused airport terminal shutdowns and passenger inconvenience. Despite the fact that the airport terminal configuration is a fundamental component of airport passenger terminal operations, previous research has focused mainly on strategies to improve passenger flow based on existing terminal designs.

The driving factors for the decisions on whether to design an airport terminal a certain way are based on cost and payback period. A New York Times study in 2005 reported that more than 25,000 security breaches in ten years have occurred at U.S. airports since November 2001—an average of about seven per day, and slightly more than five security breaches per year at each of the 457 commercial airports. The average cost of evacuation per minute—0.0336 million dollars—was calculated based on this reported data. For additional information concerning breaches, readers may consult *Aviations Operations Directive AVO400.50.1-25: Security Breach at Passenger Screening Checkpoint: Revised*.

The objective of this research is to use an integrated simulation method to develop an analysis of the relationship between arriving and departing passenger flows, and the design and operation of airport terminal facilities. This research examines the operational effects of alternative airport terminal configurations and their impact on passenger flow. The simulation approach attempts to define and institute a security-friendly airport passenger terminal structure that maximizes the passenger flow and airport operation of the new security measures.

Previous Relevant Research

As previously discussed, new security measures continue to evolve in light of global security concerns, and more airports worldwide continue to seek new technologies in their approach to airport design, planning and operations (Fayez et al., 2008). Also, the focus of commercial passenger flow research has been on strategies involving the passenger flow process of existing airport terminal layouts. One of the predominant approaches has been the use of simulation models (Fayez et al., 2011).

One early passenger flow research simulation-based effort was conducted by Chung and Nyakman (1996). The study was exclusively devoted to the operation of airport security faculties, specifically, the checkpoints, under increased threat conditions. Their work studied the processing of passengers through security checkpoints at a major metropolitan airport, and the results offered direction for airport officials in sustaining an effective passenger movement under this threat conditions. A simulation analysis was performed to assess this situation and several scenarios were developed to provide the most effective mode of operation under a variety of alternative configurations.

Gatersleben and Weij (1999) presented a dynamic simulation model used in the redesign and analysis of passenger handling at an airport. The entire concept served the objective of applying simulation to elaborate on the relationship that exists between passenger flow and the processes associated with it, existence of bottlenecks, and possible solutions. Their dynamic simulation model analyzed and evaluated, through development of scenarios, passenger flow through the terminal and the utilization of non-assignable facilities, while acknowledging their interdependency.

Valentin (2002) acknowledged the importance of applying simulation models at airports whose operations are subject to change and decision making bottlenecks. A simulation tool formed as a set of building blocks in a simulation language was used to aid the modeling of airports. The paper provided a brief description of the building blocks, their use in the simulation of passenger flows and the results of the simulation scenarios using these building blocks. Valentin acknowledged that though terminal design remained the ultimate focus, new issues such as safety or security can also be resolved using simulation.

Takakuwa and Oyama (2003) created experimental data for executing a simulation by designing and developing a special-purpose data-generator. In this way, the possible number of delayed flights is drastically reduced by increasing supporting airport staff and also by employing check-in counters, exclusively reserved for first and business class, in processing economy and group class passengers.

Olaru and Emery (2007) used a combined model of simulation and genetic algorithm (GA)-optimization to model the operation of airport passenger terminals. This combined model was used as a process of organizational change to evaluate the efficiency and performance of the airport operation, and impacts of infrastructure and operation changes.

Understanding that decision making with respect to airport terminal planning, design and operations entails significant trade-offs regarding alternative operational policies and physical terminal layout concepts, Manataki and Zografos (2009) developed a mesoscopic model for airport terminal performance analysis that finds a compromise between flexibility and realistic results, adopting a system dynamics approach. This approach facilitated model development by being adaptable to different airport terminal configurations and operational characteristics.

Problem Statement

A fundamental problem with airport security breaches is the potentially differing objectives between airport management and security authorities. The focus of airport management is to maintain operational throughput with minimum disturbance. Conversely, security authorities focus on the safety of the passengers and the infrastructure itself. The challenge is meeting the needs of both stakeholders. As described in the previous section, the focus of previous research is on the best passenger flow and operational performance within the confines of existing airport terminal configurations. In comparison, the objective of this research effort is to specifically optimize passenger flow and operational performance during a security breach by defining different possible airport terminal configurations.

Research Methodology

The research methodology consisted of system definition, input data collection and analysis, model translation, verification and validation, experimental design, and output analysis.

System Definition

The airport terminal is predominantly the key study of this research. Commercial airports are available in an exhaustive list of terminal configurations. Airport terminal concepts are categorized into three groups: horizontal, vertical and landside distributions (Trani, 2002). Horizontal distribution in which the landside configurations have either centralized or decentralized services is further broken down to the linear, pier-finger, satellite and transporter terminal concepts. The vertical distribution is used to demarcate arrival from departing flows. It provides added level of security and is divided into the following concepts: one level, one and one half levels, and two level terminals. To allow meaningful comparisons between airport terminal designs, a standard airport terminal concept was selected. The terminal used for the purpose of this research is Hobby Airport, Houston, Texas, which has a pier terminal configuration. This airport is classified by the FAA as a midsized international airport with over 4,000,000 enplanements annually through a total of 26 gates. This system was selected for data collection due to its representative size as the 33rd busiest airport in the U.S. and also due to an existing professional relationship with the researchers which facilitated access to the facility.

The simulation includes the departure of passengers as they go through the security checkpoints en-route to their departing gates with the occurrence of security breach that results in evacuation of the passengers from the secured area.

For the purpose of the study, passengers form the entities of the system. This research tries to reduce the time it takes to evacuate the passengers during a security breach by designing an optimized airport terminal configuration. This simulation assumes single passengers (batch size of 1) traveling through the system.

The events are primarily the activities involved during passenger movement through the airport terminal and his/her evacuation after a security breach. Such events include arrival and departure of passengers, security checking, and their eventual evacuation when a security breach occurs.

TABLE 1
Model Validation Data

Data Source	Mean Time in Minutes	Standard Deviation in Minutes
System	1713	948
Model	4102	1577

The system output performance is measured by service time of the activities, travel rate, walking distances, walking speeds and evacuation distance and time covered by passengers. This performance measure provides indicators to analyze the system and compare alternative configurations.

Input Data Collection and Analysis

Input data was also collected at Hobby Airport located in Houston, Texas. Data collection included both historical data and real time original observable input data. Data on entity arrival times, service times, route times, and gate schedules were collected on physical visits to the airport at one of its busiest operational times. Data on the number of passengers per flight, travel rate, and gate schedules was collected based on historical data. The variation in the different airlines that maintain operations at Hobby Airport, the number of gates, and type of airports required the use of a specific number of passengers per flight for our model to optimize its functionality. An average value of 140 was

TABLE 2
Types of Design

No.	Layout Type	TYPE OF DESIGN
1	T1	Pier Type 1 (1 Level)
2	T2	Pier Type 1 (2 Level)
3	T3	Circular Type 1 (1 Level)
4	T4	Circular Type 1 (2 Level)
5	T5	Circular Type 2 (1 Level)
6	T6	Circular Type 2 (2 Level)
7	T7	Circular Type 3 (1 Level)
8	T8	Circular Type 3 (2 Level)
9	T9	Semicircular Type 1 (1 Level)
10	T10	Semicircular Type 1 (2 Level)
11	T11	Semicircular Type 2 (1 Level)
12	T12	Semicircular Type 2 (2 Level)
13	T13	Semicircular Type 3 (1 Level)
14	T14	Semicircular Type 3 (2 Level)
15	T15	Rectangular Type 1 (1 Level)
16	T16	Rectangular Type 1 (2 Level)
17	T17	Rectangular Type 2 (1 Level)
18	T18	Rectangular Type 2 (2 Level)
19	T19	Rectangular Type 3 (1 Level)
20	T20	Rectangular Type 3 (2 Level)
21	T21	Triangular Type 1 (1 Level)
22	T22	Triangular Type 1 (2 Level)
23	T23	Triangular Type 2 (1 Level)
24	T24	Triangular Type 2 (2 Level)
25	T25	Triangular Type 3 (1 Level)
26	T26	Triangular Type 3 (2 Level)

TABLE 3
Evacuation Time Summary Statistics and Replication Requirements

Configuration	Mean Evacuation Time in Minutes	Standard Deviation of Evacuation Time in Minutes	Replications Required	Relative Precision
T1	39.23	0.63	10	0.01
T2	39.49	0.68	10	0.01
T3	38.73	0.55	10	0.01
T4	41.97	1.04	10	0.02
T5	39.53	0.69	10	0.01
T6	40.57	0.85	10	0.02
T7	40.22	0.83	10	0.01
T8	40.46	0.83	10	0.01
T9	39.95	0.92	10	0.02
T10	40.18	0.79	10	0.01
T11	39.96	0.78	10	0.01
T12	40.76	0.93	10	0.02
T13	40.40	0.84	10	0.01
T14	41.00	0.93	10	0.02
T15	38.98	0.58	10	0.01
T16	39.34	0.65	10	0.01
T17	40.14	0.81	10	0.01
T18	40.70	0.92	10	0.02
T19	40.17	0.79	10	0.01
T20	40.43	0.85	10	0.01
T21	39.10	0.61	10	0.01
T22	39.58	0.74	10	0.01
T23	39.65	0.71	10	0.01
T24	40.07	0.80	10	0.01
T25	39.42	0.62	10	0.01
T26	39.74	0.70	10	0.01

used as the number of passengers per flight for the model. The airport terminal used for this model has 25 gates of which 18 were active at the time of collecting the data used for the model. A flight schedule was obtained from airport operations that showed daily airline schedules for the different gates during peak operations. This model assumed that passengers arrive at the airport 1.5 hours before their flight departs.

Model Translation

The system was translated using the simulation software Arena distributed by Rockwell Software. Arena is a leading graphical simulation software package based on the SIMAN simulation language software originally developed in the 1980s. In its current manifestation, the software provides the ability to graphically create a model using the appropriate blocks, elements, and animation components. For ease of use and aesthetics, the simulation was divided into three major portions, consisting of the model, the experiment and animation. The experiment consists of elements used to define the general parameters experimental conditions, variables and attributes of the system and its components. The animation provides a visual or pictorial representation of the model and its entities that helped to assess the working capabilities of the system.

TABLE 4
ANOVA Results

General Linear Model: Mean (Mins) Versus Type of Desi, Number of Sh, …						
Factor	Type	Levels	Values			
Type of Design	fixed	5	Circular, Rectangular, Semicircular, Triangular, Y Pier			
Number of Shapes	fixed	3	1, 2, 3			
Level of Terminal	fixed	2	1, 2			
Analysis of Variance for Mean (mins), using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of Design	4	30.317	23.864	5.966	7.62	0.000
Number of Shapes	2	12.059	12.059	6.029	7.71	0.001
Level of Terminal	1	29.846	29.846	29.846	38.14	0.000
Error	252	197.193	197.193	0.783		
Total	259	269.416				

Model Validation

Model validation consisted of statistically comparing the rate of evacuation (number of passengers evacuated per hour) between an actual airport terminal and the simulation model. Because Hobby Airport has a pier terminal configuration, a comparison of the output of the model with data from airports with similar pier design concept was made. As a result, the available data from the system was limited to 13 observations for validation purposes. Due to the less than optimal number of rate of evacuation observations, a non-parametric rank sum test was required for the validation process.

The mean and standard deviation of the rate of evacuation for both the system and the base model are listed in Table 1. The following section summarizes the non-parametric validation process.

- H_o: The mean rate of evacuation between the system and the model is not statistically different at the given alpha level.
- H_a: The mean rate of evacuation between the system and the model is statistically significantly different at the given alpha level.
- Level of Significance, alpha = 0.05.
- Critical Value for alpha = 0.05 is ± 1.96 using the Z distribution.
- Test Statistic. The Rank Sum Test yielded a test statistic of -1.363.
- Decision. The test statistic of -1.363 was between -1.96 and +1.96. The H_o cannot be rejected.

The fact that the H_o cannot be rejected at an alpha level of 0.05 provides support for the claim that the base model is statistically valid. With a statistically valid base model, the experimental alternatives were developed.

Experimental Design

Regulatory air transportation agencies such as the DOT, FAA, TSA, and ICAO provide some design limitations and recommendations to commercial airport terminal operation. The most significant of these is FAA Advisory Circular AC 150/5360-13. The experimental layouts were developed within these recommendations. As discussed in the previous section, since Hobby Airport is a pier terminal configuration, the different experimental designs are defined based on the perspective of a pier design but designed with respect to two levels of vertical distribution (one and two level terminals) and thirteen different factors conceptualized by the shape of the terminal concept, and number of shapes.

The shapes defined include circular, semicircular, triangular and rectangular pier design concepts. The number of shapes includes one, two and three shapes. All are designed at either a one- or two-level terminal vertical

TABLE 5
Duncan Multiple Range Test Results

DUNCAN MULTIPLERANGE TEST RESULTS

	MSE	0.595		S_x=SQRT(MSE/n)																						
	n	10		S_x	0.243926																					
	DF	207																								
The Duncan Multiple Range Test multiplier table values for r between 2 and 26 at 0.05 and 120 degrees of freedom (21 through 26 interpolated) are:																										
P	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	
r	2.800	2.947	3.045	3.116	3.172	3.217	3.254	3.286	3.313	3.337	3.358	3.377	3.394	3.409	3.423	3.435	3.446	3.457	3.466	3.475	3.484	3.493	3.502	3.511	3.520	
R	**0.682993**	**0.718851**	**0.742755**	**0.760074**	**0.773734**	**0.784711**	**0.793736**	**0.801542**	**0.808128**	**0.813982**	**0.819104**	**0.823739**	**0.827886**	**0.831544**	**0.834959**	**0.837887**	**0.84057**	**0.843253**	**0.845448**	**0.847644**	**0.849839**	**0.852034**	**0.85423**	**0.856425**	**0.85862**	
Ranking	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Alternative	T3	T15	T21	T1	T16	T25	T2	T5	T22	T23	T26	T9	T11	T24	T17	T19	T10	T7	T13	T20	T8	T6	T18	T12	T14	T4
Non-Signifant Range of Adjacent Means:																										
Alternative	T3	T15	T21	T1	T16	T25	T2	T5	T22	T23	T26	T9	T11	T24	T17	T19	T10	T7	T13	T20	T8	T6	T18	T12	T14	T4
Means (mins)	38.729	38.982	39.098	39.232	39.343	39.416	39.489	39.527	39.577	39.654	39.741	39.948	39.958	40.067	40.138	40.173	40.177	40.224	40.402	40.431	40.460	40.572	40.699	40.762	41.000	41.974

distribution. A total number of 26 experimental designs, including the model, were developed (see Table 2).

Replication Analysis

Since the rate of evacuation is probabilistic, replication analysis is required in order to make a statistically robust comparison between configurations. This consists of determining the number of simulation runs or replications that are necessary at a given level of confidence. The relative precision method of replication analysis was utilized for this study. This method consists of calculating the ratio of the half-width confidence interval over the mean of the replication data.

Table 3 indicates that 10 replications were sufficient for each configuration to achieve a desired relative precision ratio of 0.10.

Discussion

The data obtained with 10 replications for each of the 26 combinations was examined using the Minitab. This test of H_0 was based upon the assumption that the data came from normally distributed populations of data, that the samples are independent, that the samples are random, and that the variances of the normally distributed populations of the data are the same (i.e., remain constant from population to population). Minitab was used to test for normality.

A multi-factor ANOVA was performed using Minitab and the results obtained are displayed Table 4. The p-value of less than 0.05 indicates there is a difference between the factor levels. The confidence intervals aid in assessing which combinations of levels are actually different.

The table indicates that, at a 0.05 level of significance, the main factor is statistically significant. This means that changing the design of the airport terminal at the different configurations will have a statistically significant impact on the time it takes to evacuate passengers from the sterile area of the terminal after a security breach. To obtain additional insight into these results, a Duncan multiple range test was performed on the alternatives, as illustrated in Table 5. This test calculates a least significant range value R for each set of adjacent means. If the range of the adjacent means exceed the critical value, the adjacent means are statistically significantly different.

The Duncan Multiple Range Tests indicate that the existing airport terminal configuration (T1) of "Y" pier

TABLE 6
Cost Analysis for All Alternatives

COST ANALYSIS OF ECONOMIC IMPACT OF ALTERNATIVE AIRPORT TERMINAL DESIGN						
Type of Design	Description	Average Evacuation Time (min)	Average Evacuation Cost Per Minute (mill./min)	Estimated Cost of Evacuation (mill.)	Estimated Cost of Evacuation Per Year in Millions (Assuming 5 occurences every year)	Estimated Cost of Evacuation Per Year in Millions for 20 Years
T1	Pier Type 1 (1 Level)	39.232	0.0336	1.3170	6.5849	131.6986
T2	Pier Type 1 (2 Level)	39.489	0.0336	1.3256	6.6281	132.5621
T3	Circular Type 1 (1 Level)	38.729	0.0336	1.3001	6.5006	130.0124
T4	Circular Type 1 (2 Level)	41.974	0.0336	1.4091	7.0453	140.9054
T5	Circular Type 2 (1 Level)	39.527	0.0336	1.3269	6.6344	132.6885
T6	Circular Type 2 (2 Level)	40.572	0.0336	1.3620	6.8099	136.1974
T7	Circular Type 3 (1 Level)	40.224	0.0336	1.3503	6.7514	135.0279
T8	Circular Type 3 (2 Level)	40.460	0.0336	1.3582	6.7911	135.8221
T9	Semicircular Type 1 (1 Level)	39.948	0.0336	1.3410	6.7051	134.1026
T10	Semicircular Type 1 (2 Level)	40.177	0.0336	1.3487	6.7436	134.8717
T11	Semicircular Type 2 (1 Level)	39.958	0.0336	1.3414	6.7068	134.1363
T12	Semicircular Type 2 (2 Level)	40.762	0.0336	1.3683	6.8417	136.8340
T13	Semicircular Type 3 (1 Level)	40.402	0.0336	1.3563	6.7814	135.6276
T14	Semicircular Type 3 (2 Level)	41.000	0.0336	1.3763	6.8817	137.6338
T15	Rectangular Type 1 (1 Level)	38.982	0.0336	1.3086	6.5431	130.8610
T16	Rectangular Type 1 (2 Level)	39.343	0.0336	1.3207	6.6036	132.0725
T17	Rectangular Type 2 (1 Level)	40.138	0.0336	1.3474	6.7370	134.7395
T18	Rectangular Type 2 (2 Level)	40.699	0.0336	1.3662	6.8311	136.6229
T19	Rectangular Type 3 (1 Level)	40.173	0.0336	1.3486	6.7430	134.8591
T20	Rectangular Type 3 (2 Level)	40.431	0.0336	1.3572	6.7861	135.7229
T21	Triangular Type 1 (1 Level)	39.098	0.0336	1.3125	6.5625	131.2503
T22	Triangular Type 1 (2 Level)	39.577	0.0336	1.3286	6.6428	132.8569
T23	Triangular Type 2 (1 Level)	39.654	0.0336	1.3312	6.6559	133.1177
T24	Triangular Type 2 (2 Level)	40.067	0.0336	1.3450	6.7252	134.5031
T25	Triangular Type 3 (1 Level)	39.416	0.0336	1.3232	6.6159	132.3185
T26	Triangular Type 3 (2 Level)	39.741	0.0336	1.3341	6.6704	133.4070

design concept, a single shape and at level 1 performs well in comparison to the other alternatives. The alternatives T3 (circular design concept, single shape at level 1), T15 (rectangular design, single shape, at level 1) and T21 (triangular design, single, at level 1) all resulted in a lower mean time than the existing airport terminal configuration. However, the Duncan test indicates that the difference between these alternatives and the present terminal concept is not significant.

The mean time of the circular design concept, single shape, at level 2 (T4) is higher, and also statistically significantly different from that of the existing concept. Hence it is seen that if the terminal configuration for this airport is a "Y" pier design with single shape and at level 1, the time to evacuate people after a security breach is significantly reduced compared to other alternatives.

Limitations and Assumptions

The input data driving the model was collected during the spring months of March to June. According to Bureau of Transportation and OAG statistics, the busiest months of airline activity are July and August. In 2009 for example, approximately 8.9% of activity was conducted each during July and August. March had 8.3%, April 8.2%, May 8.4%, and June had 8.5%. While the data was collected during the months of March to June, the difference between that period and any other periods of the year including the summer months does not appear to be statistically significantly larger not to apply the research results to other times of the year.

Conclusions

Alternatives T3, T15 and T21 have lower evacuation times than T1, the existing system, but the Duncan Test indicated that the differences are not statistically significant. The existing system therefore performs statistically well when compared to the other alternatives. Using the historically calculated average cost of evacuation per minute, we can compare the cost of evacuation over a 20 year period for each of these alternatives as shown in Table 6.

The difference in cost is not entirely significant, but from a practical level, the marginal differences in the lower evacuation times for these types compared to the existing system may be worth further consideration because this research did not factor revenues associated with concession services associated with total airport terminal area which may have a greater impact than has been statistically demonstrated.

In summary, a complete airport terminal design probably requires integration of structural design and architecture with the functional planning of passenger and operational spaces. The emphasis of this dissertation was more on the architectural/structural design of airport terminals with minor reference to operational requirements.

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